

Electrical Energy Storage

5        This invention relates to the storage of electrical energy, in particular to systems and methods for storing electrical energy in the form of chemical bonds, more particularly chemical bonds formed by reaction of hydrogen and carbon dioxide.

10      The rate of generation of electricity cannot always readily be matched with demand. For example, if electricity is generated using solar energy, maximum electricity generation occurs on warm sunny days whereas maximum electricity demand may occur when it is dark and/or cold. Similar problems are encountered with other forms of electricity generation, in particular other forms of generation such as wind or wave power where the rate of production of electricity can vary unpredictably. Even with conventional power stations which feed electricity into the national grid, electricity demand is much higher during the day than during the night. In an attempt to overcome these problems, various methods have been used for the storage of electricity.

15      Electrical energy can be stored in electrochemical batteries which store electrical energy in the form of chemical energy. Alternatively, electricity can be used, for example, to electrolyse water to produce hydrogen and oxygen and then the hydrogen can be stored in some way until demand for electricity rises. The stored hydrogen is then used to generate electricity to meet the increased demand. For example, the hydrogen 20      can be stored in a pressurised vessel, adsorbed in a metal hydride hydrogen gas adsorption storage system or cooled until it liquefies and later released for use in

- 2 -

a hydrogen fuel cell to generate electricity (see for example JP 9050820 and JP 8064220). Alternatively, it has been proposed to use hydrogen generated from the electrolysis of water to chemically reduce toluene to 5 form methylcyclohexane (Th. H. Schucan et al, Seasonal Storage of Electricity with Chemically Bound Hydrogen, Electrical Energy Storage Systems Applications Technologies Conference, Chester, UK, 16-18 June 1998). The methylcyclohexane is then stored until demand for 10 electricity increases. Dehydrogenation of the methylcyclohexane then releases hydrogen which can be used in fuel cells for the generation of electricity.

15 However, the known systems for storing electricity are expensive and inflexible and do not readily lend themselves to storing varying amounts of electrical energy over time. Thus, if batteries are to be used, a large number of batteries must be provided permanently to take into account the maximum possible electrical 20 energy which may need to be stored. Batteries also suffer from the disadvantages that they are both heavy and expensive. Similarly, hydrogen gas adsorption storage systems are inflexible and require large amounts of the adsorbing material to be ready in order to take 25 into account the maximum possible electrical energy which may need to be stored. In addition, there are safety risks associated with the storage of hydrogen gas due to its potentially explosive nature. Similarly, the toluene-methylcyclohexane system requires the 30 preliminary storage of large amounts of toluene, which is both toxic and flammable, in readiness for use to store electrical energy.

35 There is therefore still a need for a system and methods for storing electrical energy which are flexible, environmentally friendly and easily adaptable to widely differing rates of electricity generation.

- 3 -

According to one aspect of the present invention, there is therefore provided a system for the storage of electrical energy, said system comprising electrolysis means connectable to supplies of water and electricity and operable to provide the electrolysis of water to generate hydrogen, reaction means for receiving hydrogen generated by said electrolysis means, the reaction means providing the reaction of said hydrogen with carbon dioxide to form a storage compound, means for the supply of carbon dioxide to said reaction means, and storage means connected to said reaction means for the storage of said storage compound. As discussed below, the system preferably further comprises regeneration means for the generation of electrical energy either directly or indirectly from the storage compound.

As used herein, a storage compound is any carbon-containing compound that may be produced via the reaction of hydrogen and carbon dioxide, or from the further reaction of methanol produced by the initial reaction of carbon dioxide and hydrogen, for example an organic compound such as methanol or a higher alcohol (e.g. a C<sub>2-8</sub> alcohol), preferably methanol, a Fischer-Tropsch liquid, Mobil gasoline, or a C<sub>1-8</sub> acid, C<sub>1-8</sub>-aldehyde, C<sub>1-8</sub>-ether or C<sub>1-8</sub>-hydrocarbon, preferably a C<sub>1-4</sub> acid, C<sub>1-4</sub>-aldehyde, C<sub>1-4</sub>-ether or C<sub>1-4</sub>-hydrocarbon, more preferably a C<sub>1</sub>-acid, C<sub>1</sub>-aldehyde, C<sub>1</sub>-ether or C<sub>1</sub>-hydrocarbon. Methanol is an especially preferred storage compound. The storage compound may be a gas, liquid or solid under standard conditions of temperature and pressure. For ease of transfer and storage, the storage compound is preferably a liquid under standard conditions. The storage compound may be formed as a mixture with water and may optionally be stored as such a mixture rather than being separated from the water and dried.

PCT/GB99/03547

The electricity supply may be of any form, for example the mains grid. The system may itself further comprise electricity generating means, whereby electricity may be generated and supplied to the 5 electrolysis means. Such electricity generating means may be any conventional generating means. Examples of suitable generating means include solar panels, wind-powered generators and wave-powered generators. These are particularly suitable for use in the 10 invention. Solar panels are preferred generating means.

The water supply means may be any source of water connectable to the system, for example the mains water supply connected via a suitable deioniser. 15 Alternatively, a tank of de-ionised water may be provided for connection to the system. In a domestic setting, the water supply may suitably be water from the household supply which has been de-ionised using conventional methodology. Commercially available water 20 electrolysis units often comprise a suitable deioniser so that they may use mains water.

Suitable electrolysis means for the electrolysis of water are known in the art. Suitable equipment is 25 commercially available for example from the company Teledyne Brown Engineering of Maryland, U.S.A..

The reaction means may be any means suitable for the reaction of hydrogen with carbon dioxide to form a 30 storage compound. Suitable means are known in the art. The means optionally comprise one or more catalysts, and are optionally supplied with heating and pressurizing means. Catalysts and conditions for the reaction of hydrogen with carbon dioxide to form suitable storage 35 compounds are well known in the art (see for example The Catalyst Handbook, 2nd Ed., Ed. M.V. Twigg, Oxford University Press, 1997; GB 1 595 413). More than one

- 5 -

type of catalyst may be present in the reaction means, for example in a series of catalyst beds, in order to convert any initial reaction products produced by reaction of hydrogen with carbon dioxide into the desired storage compound. For example, Fischer-Tropsch liquids may be produced by the further reaction of hydrogen with initially formed carbon monoxide, whilst Mobil gasoline may be produced by the further reaction of initially formed methanol.

10

Alternatively, the reaction means and the electrolysis means may be combined such that a storage compound is formed by direct electrochemical conversion is an aqueous carbon dioxide-containing electrolyte using a suitable electrode (see for example Bandi et al., J. Electrochem. Soc., 1990, 137, 2157-2160, Frese et al., J. Electrochem. Soc., 1984, 131, 2518-22, Hori et al., Chem. Lett. 1986, 897-898, Kaputsa et al., J. Electrochem. Soc., 1983, 130, 607-613, Ogura et al., Solar Energy, 1986, 37, 41-45).

15

20

The hydrogen produced in the electrolysis means may be fed directly to the reaction means. Alternatively, the system may optionally comprise means, for example a pressurised cylinder or tank, for the temporary storage of hydrogen before it is fed into the reaction means.

25

The carbon dioxide supply means may comprise means for the extraction of carbon dioxide from the air. Such extraction means are known in the art (Y. Hirayama et al, Proceedings of the Second International Conference on Carbon Dioxide Removal (ICCDR-2), 435-438, 419-422 (1995) and Polymeric Gas Separation Membranes by Robert E. Kesting, Ed. A.K. Fritzsche, John Wiley & Sons (1993)). For example, membranes which may be used for the extraction of carbon dioxide from gaseous mixtures are available commercially from Kvaerner Membrane

100 90 80 70 60 50 40 30 20 10 0

- 6 -

Systems of Houston, Texas. Alternatively or additionally, the carbon dioxide supply means may comprise means for attachment to a store of carbon dioxide which may be stored in gaseous, liquid or solid form. Carbon dioxide is available commercially in gaseous, liquid or solid form.

The carbon dioxide supply means may alternatively comprise means for the extraction of carbon dioxide from power station flue gases or other industrial exhaust gases using known methodology (see for example Carbon Dioxide Removal from Coal Fired Power Plants (Energy and Environment Vol 1) by Chris Hendriks, Kluwer Academic Publications (1994)). Typically, carbon dioxide may comprise 5-25% of such flue gases.

The storage means may be any means suitable for the storage of the storage compound, for example tanks, drums or the like. The storage means may be any suitable size taking into account the maximum amount of electrical energy it is desired to store at any one stage. For example, a system for domestic use may involve a storage means of sufficient size to merely store excess electrical energy produced from a solar panel during the course of a day for generation of electricity during the night. In a larger system, a correspondingly larger store may be needed. The storage means may be at some distance from the reaction means and the system may further comprise one or more pumps or other suitable means for the transfer of the storage compound from the reaction means to the storage means. For example, in a domestic system, the storage means may comprise a tank buried in the garden of the house, whilst the electrolysis and reaction means may be located inside the house or garage.

A preferred embodiment of the system further

102200-3000850

- 7 -

comprises regeneration means for the generation of electrical energy either directly or indirectly from the storage compound. If necessary, a pump or other suitable means may be provided to transfer the storage 5 compound from the storage means to the regeneration means. The regeneration means may comprise a suitable fuel cell for the conversion of the storage compound directly to electrical energy. For example, US 4524113 discloses a methanol fuel cell. Methanol fuel cells may 10 be used if the storage compound is methanol. If oxygen is required for the functioning of the fuel cell, it may be in the form of oxygen from the air. Alternatively, the regeneration means may comprise a conventional internal combustion engine or other suitable generator 15 in which the storage compound may be used as a fuel.

If carbon dioxide is produced as a by-product from the fuel cell or generator it may be recycled to the reaction means for reaction with further hydrogen. In 20 such circumstances, the carbon dioxide supply means may comprise means for the recycling of carbon dioxide from the fuel cell or generator.

Alternatively, the regeneration means may comprise 25 further reaction means whereby the storage compound may be converted back into hydrogen and, optionally, carbon dioxide, optionally together with a hydrogen fuel cell or other suitable means for the conversion of the hydrogen into electricity (see for example GB 1165679). 30 If the system comprises further reaction means to convert the storage compound back into hydrogen, then the system may be used for the storage of hydrogen. Such a system for the storage of hydrogen forms a further feature of the invention. If the system is to 35 be used for the storage of hydrogen, then the electrolysis means may be replaced by some other source of hydrogen connectable to the reaction means.

TOP SECRET - SECURITY INFORMATION

The further reaction means may be any means suitable for the conversion of the storage compound into hydrogen and optionally carbon dioxide. Suitable means are known in the art and include steam reformers.

5      Suitable catalysts to catalyse the conversion are also known in the art. Suitable hydrogen fuel cells are also known in the art, for example those available commercially from Ballard Power Systems Inc. of British Columbia, Canada. The carbon dioxide so produced may be separated and recycled for reaction with further 10     hydrogen. In such circumstances, the carbon dioxide supply means may comprise means for the recycling of carbon dioxide from the regeneration means.

15     The regeneration means may also comprise means whereby any by-products or unreacted starting materials from the conversion of the storage compound back into hydrogen and carbon dioxide may be removed before the hydrogen is introduced into a hydrogen fuel cell. For 20     example, means for the catalytic oxidation of carbon monoxide may be included.

The electricity generated from the storage means may be used to meet domestic or commercial demand. 25     Alternatively, the regeneration means could comprise part of a vehicle and the electricity could be used to power the vehicle.

30     In another preferred embodiment, the system of the invention further comprises an internal combustion engine in which the storage compound or storage compound/water mixture may be used as a fuel. The internal combustion engine may be used to power for example a vehicle.

35     In another embodiment of the invention, the system further comprises a further reaction means whereby the

- 9 -

storage compound or storage compound/water mixture may be reacted under suitable condition to produce other chemical compounds. Such compounds could be useful as fuels or could be sold as industrial feedstocks.

5

Preferably, the system is fully automated and its operation is controlled by a suitable control system, for example a microprocessor and the necessary circuitry.

10

The invention extends to a method for the storage of electrical energy utilising carbon dioxide and water, the method comprising the following steps:

15

- (a) electrolysis of water to yield hydrogen;
- (b) reaction of the hydrogen from step (a) with carbon dioxide to form at least one storage compound, optionally in a mixture with water;
- (c) storage of said storage compound or storage compound/water mixture; and
- (d) subsequent use of said storage compound or storage compound/water mixture to fuel an internal combustion engine or to generate electricity either directly or indirectly.

20

The method and system of the invention utilise readily available compounds, namely water and carbon dioxide, in the storage of electricity. Both compounds are cheap, readily available, and pose no particular storage problems. Electrical energy is stored in the form of chemical energy in the bonds of a suitable storage compound formed by the reaction of hydrogen with carbon dioxide.

25

The electrolysis of water may be carried out using conventional electrolysis technology. The electrolysis of water produces hydrogen which is retained for further

- 10 -

reaction and oxygen which may be released to the air. Preferably, the efficiency of the electrolysis step is about 80% or greater.

5        The hydrogen generated from the electrolysis step is then reacted with carbon dioxide to form a storage compound as hereinbefore defined. Water may also be produced as a by-product of the reaction. The storage compound may be a gas, liquid or solid under standard 10 conditions of temperature and pressure. For ease of transfer and storage, the storage compound is preferably a liquid under standard conditions.

15        Catalysts and conditions for the reaction of hydrogen with carbon dioxide to form suitable storage compounds are well known in the art (see for example The Catalyst Handbook, 2nd Ed., Ed. M.V. Twigg, Oxford University Press, 1997; GB 1 595 413). For example, for the reaction of hydrogen and carbon dioxide to produce 20 methanol, a temperature range of about 210-300°C, preferably 240-280°C, and a pressure of about  $5 \times 10^6$  -  $1 \times 10^7$  Pa (50-100 bar) preferably  $6 \times 10^6$  -  $9 \times 10^6$  Pa (60-90 bar) are suitable. The catalyst may be a conventional zinc oxide/copper/alumina 25 catalyst, for example a catalyst comprising approximately 60% by weight copper, 30% by weight zinc oxide and 10% by weight alumina. Suitable catalysts include those available commercially from ICI under the trade name "51 Series".

30        The carbon dioxide used in step (b) may be extracted from the air as required using known methodology. Alternatively or additionally, carbon dioxide may be stored in gaseous, liquid or solid form, 35 ready for reaction as required. The major side product of the reaction of carbon dioxide and hydrogen is water, which may be separated from the storage compound and

5 safely released to the environment or recycled for use in the electrolysis step. Alternatively, the water may be retained in admixture with the storage compound, for example as a useful component in a subsequent energy regeneration step. This has the advantage that separation of water from the storage compound is not necessary.

10 The storage compound may be purified if necessary, for example by purging of unreacted hydrogen and carbon dioxide and/or by removing water or other reaction by-products. Such purged gases may then be recycled for further use in step (b) of the method of the invention, whilst any water may be recycled for use in step (a).

15 Electrical energy is stored in the form of chemical energy in the bonds of the storage compound. The storage compound may be stored, for example in a storage tank, until there is a need for electricity to be regenerated by releasing the energy stored in said chemical bonds. The period of storage will depend on the circumstances but may vary from a few hours to weeks or months. The storage means may be any means suitable for the storage of such compounds, for example tanks, drums or the like. The storage means may be any suitable size taking into account the maximum amount of electrical energy it is desired to store at any one time. For example, a system for domestic use may involve a storage means of sufficient size to merely store excess electrical energy produced from a solar panel during the course of a day for generation of electricity during the day. Alternatively, it may be desired to store energy produced from solar panels (or any other source of electricity) during the summer for use in the winter, in which case larger storage means are required. The method of the invention therefore provides a flexible method for the storage of electrical

TOP SECRET - SECURITY INFORMATION

energy.

When demand for electrical energy increases, the energy stored in the chemical bonds of the storage compound may be released and used to generate electricity either directly or indirectly. For example, with suitable catalysts the storage compound or storage compound/water mixture may be converted back into carbon dioxide and hydrogen in a reverse of the original formation reaction and the hydrogen then used in a fuel cell or other suitable means to generate electricity. The hydrogen may need to be further processed to ensure that it does not contain quantities of carbon dioxide or carbon monoxide which may interfere with the functioning of the fuel cell. These gases may be removed using commercially available means such as the membrane systems available from Kvaerner or by using the processes disclosed in M. Iwase and S. Kawatsu, Proceedings of the 29th International Symposium on Automotive Technology and Automation: Electric, Hydrid and Alternative Fuel Vehicles, p 295, June 1996, and Initial Conceptual Design Report, Allison Engine Company for US Dept of Energy DOE/CH/10435-01, February 1994. If oxygen is required for the functioning of the fuel cell, it may be taken from the air.

Alternatively, if suitable fuel cells are available, the storage compound may be used directly in a fuel cell. For example, methanol fuel cells are known in the art (see US 4524113 for an example of a methanol fuel cell). Carbon dioxide may be one of the by-products of a methanol fuel cell.

A storage compound or a storage compound/water mixture may also be used as fuel in an internal combustion engine or other suitable generator to produce electricity.

5 If the storage compound is converted back into hydrogen and carbon dioxide, or if a fuel cell or generator produces carbon dioxide as a by-product, there  
10 is an added advantage in that the carbon dioxide so produced may be recycled for reaction with further hydrogen. The carbon dioxide used in step (b) may therefore comprise recycled carbon dioxide. In a preferred embodiment, the carbon dioxide in step (b) comprises recycled carbon dioxide topped up if required by carbon dioxide extracted from the air.

15 Both hydrogen and methanol fuel cells generate water as a by-product, which may be released to the environment or recycled for use in the electrolysis step to generate further hydrogen.

20 The electrical energy for use in the electrolysis of water in step (a) may be generated by any conventional generating means. However, the method of the invention is particularly suitable for use in storing electricity produced by renewable energy sources, for example solar energy, wind power or wave power, where the amount of electricity generated is  
25 highly unpredictable or varies substantially with the time of day or the time of year. The method may also be useful for the storage of electricity generated by nuclear or oil, gas or coal fired power stations during periods of low demand, ready for feeding back into the national grid at times of higher demand. Electrical energy generation using renewable energy sources is  
30 preferred.

35 The use of methanol as the storage compound, either alone or in admixture with water, in the methods of the invention is preferred. Methanol and water may be produced via the reaction of hydrogen with carbon

2020095000850

- 14 -

5 dioxide. Catalysts for this reaction are well known in the art and are commercially available. Fuel cells for the direct conversion of methanol to electricity are also known. Alternatively, methanol or methanol/water mixtures may be converted back into hydrogen and carbon dioxide. The hydrogen may be used in a fuel cell whilst the carbon dioxide may be recycled for reaction with further hydrogen to generate further methanol.

10 According to a further feature of the present invention, there is therefore provided a further method for the storage of electrical energy, said method comprising the following steps:

15 (a) electrolysis of water to yield hydrogen;  
(b) reaction of the hydrogen from step (a) to form a methanol/water mixture;  
(c) storage of the methanol/water mixture; and  
(d) subsequent use of the methanol/water mixture in an  
20 internal combustion engine or to generate electricity either directly or indirectly.

Again, the electricity used in step (a) may be generated by any conventional generating means.

25 Electrical energy generation using renewable energy sources is preferred. In step (b), the hydrogen is preferably reacted with carbon dioxide.

30 Methanol is a useful chemical in its own right. Rather than use methanol generated by any of the above methods for conversion into electricity, it may be sold as an industrial feedstock or used as a fuel in for example an internal combustion engined vehicle.

35 In addition to methanol being a useful chemical in its own right, hydrogen is also an important industrial feedstock. The storage of hydrogen gas is

- 15 -

complicated by its potentially explosive nature and the fact that it must be stored under pressure or as a cryogenic liquid. Rather than using the hydrogen regenerated in any of the methods of the invention to power a fuel cell, it can be used for other uses, for example as an industrial feedstock.

According to a further feature of the present invention, there is therefore provided a method for the production and storage of hydrogen, said method comprising the following steps:

- (a) electrolysis of water to yield hydrogen;
- 15 (b) reaction of the hydrogen from step (a) with carbon dioxide to form at least one storage compound;
- (c) storage of said storage compound; and
- 20 (d) subsequent conversion of said storage compound back into hydrogen and optionally also carbon dioxide.

Again, the electricity used in step (a) may be generated by any conventional generating means. Electrical energy generation using renewable energy sources is preferred. If water is formed as a by-product of the reaction of hydrogen and carbon dioxide, the storage compound may be formed, stored and used in the form of a mixture with water.

30 A preferred storage compound for the storage of hydrogen is methanol, optionally in the form of a mixture with water.

35 The hydrogen storage method of the invention has the advantage that it is flexible and readily adaptable to the storage of varying amounts of hydrogen. Rather

PCT/GB99/03547

than being stored as a potentially explosive gas, the hydrogen is stored in the form of a storage compound or storage compound/water mixture. The storage compound may be a gas, liquid or solid under standard conditions 5 of temperature and pressure. For ease of transfer and storage, the storage compound is preferably a liquid under standard conditions.

10 The use of a storage compound to store the hydrogen also has the advantage that the hydrogen can be transported whilst it is in the form of the storage compound or a storage compound/water mixture, thus avoiding the potential hazards of transporting hydrogen gas under pressure or as a cryogenic liquid.

15 The invention will be further illustrated, by way of example, with reference to the following Drawings:

20 Figure 1 illustrates in schematic form one embodiment of an electrical energy storage system according to the invention;

25 Figure 2 illustrates in schematic form the processing steps in an embodiment of the electrical energy storage method of the invention wherein the storage compound is methanol, optionally in a mixture with water; and

30 Figure 3 illustrates in schematic form an example of the component layout for an embodiment of an automated electrical energy storage system according to the invention wherein methanol is the storage compound optionally in a mixture with water;

35 Figure 4 illustrates in schematic form an example of the component layout of a regeneration means of an embodiment of an energy storage system according to the

- 17 -

invention wherein methanol is the storage compound and is stored and used as a mixture with water.

Figure 1 illustrates in schematic form one embodiment of an electrical energy storage system according to the invention. Water, for example from the mains supply, is supplied via inlet 1 to a water storage tank 2. The water is deionised in a deioniser 3 of a known type and then supplied to a hydrogen generator 4, 5 also of a known type, comprising a unit for the electrolysis of water. In the hydrogen generator, water is electrolysed to produce oxygen, which is discharged through outlet 5, and hydrogen which is fed through outlet 6 to a dryer 7. The dryer 7 is optional, as it is not essential that the hydrogen be dried. After 10 drying, the hydrogen is fed through a compressor 8 to a pressurised hydrogen storage means 9. The hydrogen is reacted with carbon dioxide in a microreactor 10 containing a suitable catalyst to form a storage 15 compound, for example methanol, optionally in a mixture with water. Pipe 11 carries the storage compound or storage compound/water mixture as well as some unreacted hydrogen and carbon dioxide to purification means 12. Purified storage compound or storage compound/water 20 mixture is fed through pipe 13 to a suitable storage means (not shown), such as a tank, whilst any unreacted gases are separated by the purification means and are recycled to the reactor 10 via pipe 14.

To generate electricity, storage compound or storage compound/water mixture is returned from the storage means via pipe 21 to regeneration means 22. The regeneration means 22 comprises a suitable fuel cell, and optionally a reactor, to convert the storage 30 compound or storage compound/water mixture back into carbon dioxide and hydrogen. Fuel cells and reactors suitable for this purpose are known. Carbon dioxide 35

- 18 -

generated by operation of the regeneration means may be recycled via pipe 23 and compressor 8' to a pressurised storage vessel 20. Carbon dioxide is supplied to the microreactor 10 from pressurised storage vessel 20. In  
5 addition to recycled carbon dioxide, the storage vessel 20 is supplied from an initial carbon dioxide store 15 and/or a carbon dioxide/air separation means 17. The separation means 17 may comprise a suitable membrane, plus an air supply inlet 16 and an outlet 19 for carbon  
10 dioxide-free air.

Water produced in the regeneration means 22 may be recycled via pipe 24 to the water storage tank 2.

15 Figure 2 illustrates in schematic form an embodiment of the electrical energy storage method of the invention wherein the storage compound is methanol or a methanol/water mixture. Sunlight falling on solar panels is used to generate electricity. The electricity  
20 is used to electrolyse water to produce hydrogen and oxygen. The hydrogen is reacted with carbon dioxide to produce methanol or a methanol/water mixture. The carbon dioxide may have been recycled, extracted from the air or brought in from outside the system. The methanol or methanol/water mixture may be stored in a tank, and then used as required, either directly in a methanol fuel cell to produce electricity, or  
25 dissociated into hydrogen and carbon dioxide, with the hydrogen then used in a hydrogen fuel cell. In either case, electricity is generated and water is a side product. The water may be released to the environment or recycled for use in the electrolysis step if desired.  
30

35 Figure 3 illustrates in schematic form a component layout for one embodiment of an automated electrical energy storage system according to the invention wherein methanol is the storage compound. The main components

- 19 -

of the system are provided in a cabinet which in a domestic system, it is envisaged, might be of similar dimensions to a refrigerator. Electricity supply means 25 supply electrical energy, for example solar energy, to the system. Water is introduced into the system via inlet 1. The electrical energy is used to electrolyse water to produce hydrogen and oxygen, and the oxygen is released to the atmosphere via outlet 5. The hydrogen is reacted with carbon dioxide, introduced via inlet 26, 10 to produce methanol or a methanol/water mixture via a series of reaction steps. The methanol may be transferred via inlet and outlet means 13, 21 to and from suitable storage means (not shown) as required. The methanol or methanol/water mixture may be used 15 directly in a methanol fuel cell to produce electricity or dissociated into hydrogen and carbon dioxide and the hydrogen used in a hydrogen fuel cell. Electricity is supplied from the system via line 27.

20 Figure 4 illustrates in schematic form a component layout for a regeneration means according to one embodiment of an electrical energy storage system according to the invention. The storage compound is methanol. A mixture of methanol and water is produced 25 and stored in a storage means (not shown). The methanol/water mixture is supplied via pipe 21 to a steam reformer 28 in which the methanol/water mixture is converted back into hydrogen and carbon dioxide. The product stream from the steam reformer which contains 30 carbon dioxide and hydrogen passes through an air cooler 33 to remove unreacted water and a separation system 29, for example a membrane system, to remove the carbon dioxide. The recovered carbon dioxide is returned to a storage tank (not shown) for use in the production of 35 further methanol. The recycled carbon dioxide may be topped up as necessary via pipe 32 from a source of supplementary CO<sub>2</sub> (not shown).

TOP SECRET - SECURITY INFORMATION

- 20 -

After removal of the carbon dioxide, hydrogen gas is passed through a catalytic oxidizer 31 to convert any carbon monoxide to carbon dioxide. Carbon monoxide may interfere with the functioning of the fuel cell 30. The 5 hydrogen is then converted to electricity in a fuel cell stack 30. The exhaust from the fuel cell may be released into the atmosphere, optionally after extraction and recycling of any carbon dioxide present.

10 The invention will be further illustrated by reference to the following non-limiting Examples.

Examples

15 The Examples illustrate the use of a domestic electrical energy storage system according to the invention which uses methanol or a methanol/water mixture to store off-peak or solar generated 20 electricity. A typical house in Miami is used to illustrate the working of the system with varying amounts of sunlight. It is assumed that solar panels cover the whole of the house roof area in the Example.

16

17  
18  
19  
20  
21  
22  
23  
24  
25  
26  
27  
28  
29  
30  
31  
32  
33  
34  
35  
36  
37  
38  
39  
40  
41  
42  
43  
44  
45  
46  
47  
48  
49  
50  
51  
52  
53  
54  
55  
56  
57  
58  
59  
60  
61  
62  
63  
64  
65  
66  
67  
68  
69  
70  
71  
72  
73  
74  
75  
76  
77  
78  
79  
80  
81  
82  
83  
84  
85  
86  
87  
88  
89  
90  
91  
92  
93  
94  
95  
96  
97  
98  
99  
100  
101  
102  
103  
104  
105  
106  
107  
108  
109  
110  
111  
112  
113  
114  
115  
116  
117  
118  
119  
120  
121  
122  
123  
124  
125  
126  
127  
128  
129  
130  
131  
132  
133  
134  
135  
136  
137  
138  
139  
140  
141  
142  
143  
144  
145  
146  
147  
148  
149  
150  
151  
152  
153  
154  
155  
156  
157  
158  
159  
160  
161  
162  
163  
164  
165  
166  
167  
168  
169  
170  
171  
172  
173  
174  
175  
176  
177  
178  
179  
180  
181  
182  
183  
184  
185  
186  
187  
188  
189  
190  
191  
192  
193  
194  
195  
196  
197  
198  
199  
200  
201  
202  
203  
204  
205  
206  
207  
208  
209  
210  
211  
212  
213  
214  
215  
216  
217  
218  
219  
220  
221  
222  
223  
224  
225  
226  
227  
228  
229  
230  
231  
232  
233  
234  
235  
236  
237  
238  
239  
240  
241  
242  
243  
244  
245  
246  
247  
248  
249  
250  
251  
252  
253  
254  
255  
256  
257  
258  
259  
259  
260  
261  
262  
263  
264  
265  
266  
267  
268  
269  
270  
271  
272  
273  
274  
275  
276  
277  
278  
279  
280  
281  
282  
283  
284  
285  
286  
287  
288  
289  
290  
291  
292  
293  
294  
295  
296  
297  
298  
299  
300  
301  
302  
303  
304  
305  
306  
307  
308  
309  
309  
310  
311  
312  
313  
314  
315  
316  
317  
318  
319  
319  
320  
321  
322  
323  
324  
325  
326  
327  
328  
329  
329  
330  
331  
332  
333  
334  
335  
336  
337  
338  
339  
339  
340  
341  
342  
343  
344  
345  
346  
347  
348  
349  
349  
350  
351  
352  
353  
354  
355  
356  
357  
358  
359  
359  
360  
361  
362  
363  
364  
365  
366  
367  
368  
369  
369  
370  
371  
372  
373  
374  
375  
376  
377  
378  
379  
379  
380  
381  
382  
383  
384  
385  
386  
387  
388  
389  
389  
390  
391  
392  
393  
394  
395  
396  
397  
398  
399  
399  
400  
401  
402  
403  
404  
405  
406  
407  
408  
409  
409  
410  
411  
412  
413  
414  
415  
416  
417  
418  
419  
419  
420  
421  
422  
423  
424  
425  
426  
427  
428  
429  
429  
430  
431  
432  
433  
434  
435  
436  
437  
438  
439  
439  
440  
441  
442  
443  
444  
445  
446  
447  
448  
449  
449  
450  
451  
452  
453  
454  
455  
456  
457  
458  
459  
459  
460  
461  
462  
463  
464  
465  
466  
467  
468  
469  
469  
470  
471  
472  
473  
474  
475  
476  
477  
478  
479  
479  
480  
481  
482  
483  
484  
485  
486  
487  
488  
489  
489  
490  
491  
492  
493  
494  
495  
496  
497  
498  
499  
499  
500  
501  
502  
503  
504  
505  
506  
507  
508  
509  
509  
510  
511  
512  
513  
514  
515  
516  
517  
518  
519  
519  
520  
521  
522  
523  
524  
525  
526  
527  
528  
529  
529  
530  
531  
532  
533  
534  
535  
536  
537  
538  
539  
539  
540  
541  
542  
543  
544  
545  
546  
547  
548  
549  
549  
550  
551  
552  
553  
554  
555  
556  
557  
558  
559  
559  
560  
561  
562  
563  
564  
565  
566  
567  
568  
569  
569  
570  
571  
572  
573  
574  
575  
576  
577  
578  
579  
579  
580  
581  
582  
583  
584  
585  
586  
587  
588  
589  
589  
590  
591  
592  
593  
594  
595  
596  
597  
598  
599  
599  
600  
601  
602  
603  
604  
605  
606  
607  
608  
609  
609  
610  
611  
612  
613  
614  
615  
616  
617  
618  
619  
619  
620  
621  
622  
623  
624  
625  
626  
627  
628  
629  
629  
630  
631  
632  
633  
634  
635  
636  
637  
638  
639  
639  
640  
641  
642  
643  
644  
645  
646  
647  
648  
649  
649  
650  
651  
652  
653  
654  
655  
656  
657  
658  
659  
659  
660  
661  
662  
663  
664  
665  
666  
667  
668  
669  
669  
670  
671  
672  
673  
674  
675  
676  
677  
678  
679  
679  
680  
681  
682  
683  
684  
685  
686  
687  
688  
689  
689  
690  
691  
692  
693  
694  
695  
696  
697  
698  
698  
699  
699  
700  
701  
702  
703  
704  
705  
706  
707  
708  
709  
709  
710  
711  
712  
713  
714  
715  
716  
717  
718  
719  
719  
720  
721  
722  
723  
724  
725  
726  
727  
728  
729  
729  
730  
731  
732  
733  
734  
735  
736  
737  
738  
739  
739  
740  
741  
742  
743  
744  
745  
746  
747  
748  
749  
749  
750  
751  
752  
753  
754  
755  
756  
757  
758  
759  
759  
760  
761  
762  
763  
764  
765  
766  
767  
768  
769  
769  
770  
771  
772  
773  
774  
775  
776  
777  
778  
779  
779  
780  
781  
782  
783  
784  
785  
786  
787  
788  
789  
789  
790  
791  
792  
793  
794  
795  
796  
797  
798  
798  
799  
799  
800  
801  
802  
803  
804  
805  
806  
807  
808  
809  
809  
810  
811  
812  
813  
814  
815  
816  
817  
818  
819  
819  
820  
821  
822  
823  
824  
825  
826  
827  
828  
829  
829  
830  
831  
832  
833  
834  
835  
836  
837  
838  
839  
839  
840  
841  
842  
843  
844  
845  
846  
847  
848  
849  
849  
850  
851  
852  
853  
854  
855  
856  
857  
858  
859  
859  
860  
861  
862  
863  
864  
865  
866  
867  
868  
869  
869  
870  
871  
872  
873  
874  
875  
876  
877  
878  
879  
879  
880  
881  
882  
883  
884  
885  
886  
887  
888  
889  
889  
890  
891  
892  
893  
894  
895  
896  
897  
898  
898  
899  
899  
900  
901  
902  
903  
904  
905  
906  
907  
908  
909  
909  
910  
911  
912  
913  
914  
915  
916  
917  
918  
919  
919  
920  
921  
922  
923  
924  
925  
926  
927  
928  
929  
929  
930  
931  
932  
933  
934  
935  
936  
937  
938  
939  
939  
940  
941  
942  
943  
944  
945  
946  
947  
948  
949  
949  
950  
951  
952  
953  
954  
955  
956  
957  
958  
959  
959  
960  
961  
962  
963  
964  
965  
966  
967  
968  
969  
969  
970  
971  
972  
973  
974  
975  
976  
977  
978  
979  
979  
980  
981  
982  
983  
984  
985  
986  
987  
988  
989  
989  
990  
991  
992  
993  
994  
995  
996  
997  
998  
998  
999  
999  
1000  
1001  
1002  
1003  
1004  
1005  
1006  
1007  
1008  
1009  
1009  
1010  
1011  
1012  
1013  
1014  
1015  
1016  
1017  
1018  
1019  
1019  
1020  
1021  
1022  
1023  
1024  
1025  
1026  
1027  
1028  
1029  
1029  
1030  
1031  
1032  
1033  
1034  
1035  
1036  
1037  
1038  
1039  
1039  
1040  
1041  
1042  
1043  
1044  
1045  
1046  
1047  
1048  
1049  
1049  
1050  
1051  
1052  
1053  
1054  
1055  
1056  
1057  
1058  
1059  
1059  
1060  
1061  
1062  
1063  
1064  
1065  
1066  
1067  
1068  
1069  
1069  
1070  
1071  
1072  
1073  
1074  
1075  
1076  
1077  
1078  
1079  
1079  
1080  
1081  
1082  
1083  
1084  
1085  
1086  
1087  
1088  
1089  
1089  
1090  
1091  
1092  
1093  
1094  
1095  
1096  
1097  
1098  
1098  
1099  
1099  
1100  
1101  
1102  
1103  
1104  
1105  
1106  
1107  
1108  
1109  
1109  
1110  
1111  
1112  
1113  
1114  
1115  
1116  
1117  
1118  
1119  
1119  
1120  
1121  
1122  
1123  
1124  
1125  
1126  
1127  
1128  
1129  
1129  
1130  
1131  
1132  
1133  
1134  
1135  
1136  
1137  
1138  
1139  
1139  
1140  
1141  
1142  
1143  
1144  
1145  
1146  
1147  
1148  
1149  
1149  
1150  
1151  
1152  
1153  
1154  
1155  
1156  
1157  
1158  
1159  
1159  
1160  
1161  
1162  
1163  
1164  
1165  
1166  
1167  
1168  
1169  
1169  
1170  
1171  
1172  
1173  
1174  
1175  
1176  
1177  
1178  
1179  
1179  
1180  
1181  
1182  
1183  
1184  
1185  
1186  
1187  
1188  
1189  
1189  
1190  
1191  
1192  
1193  
1194  
1195  
1196  
1197  
1198  
1198  
1199  
1199  
1200  
1201  
1202  
1203  
1204  
1205  
1206  
1207  
1208  
1209  
1209  
1210  
1211  
1212  
1213  
1214  
1215  
1216  
1217  
1218  
1219  
1219  
1220  
1221  
1222  
1223  
1224  
1225  
1226  
1227  
1228  
1229  
1229  
1230  
1231  
1232  
1233  
1234  
1235  
1236  
1237  
1238  
1239  
1239  
1240  
1241  
1242  
1243  
1244  
1245  
1246  
1247  
1248  
1249  
1249  
1250  
1251  
1252  
1253  
1254  
1255  
1256  
1257  
1258  
1259  
1259  
1260  
1261  
1262  
1263  
1264  
1265  
1266  
1267  
1268  
1269  
1269  
1270  
1271  
1272  
1273  
1274  
1275  
1276  
1277  
1278  
1279  
1279  
1280  
1281  
1282  
1283  
1284  
1285  
1286  
1287  
1288  
1289  
1289  
1290  
1291  
1292  
1293  
1294  
1295  
1296  
1297  
1298  
1298  
1299  
1299  
1300  
1301  
1302  
1303  
1304  
1305  
1306  
1307  
1308  
1309  
1309  
1310  
1311  
1312  
1313  
1314  
1315  
1316  
1317  
1318  
1319  
1319  
1320  
1321  
1322  
1323  
1324  
1325  
1326  
1327  
1328  
1329  
1329  
1330  
1331  
1332  
1333  
1334  
1335  
1336  
1337  
1338  
1339  
1339  
1340  
1341  
1342  
1343  
1344  
1345  
1346  
1347  
1348  
1349  
1349  
1350  
1351  
1352  
1353  
1354  
1355  
1356  
1357  
1358  
1359  
1359  
1360  
1361  
1362  
1363  
1364  
1365  
1366  
1367  
1368  
1369  
1369  
1370  
1371  
1372  
1373  
1374  
1375  
1376  
1377  
1378  
1379  
1379  
1380  
1381  
1382  
1383  
1384  
1385  
1386  
1387  
1388  
1389  
1389  
1390  
1391  
1392  
1393  
1394  
1395  
1396  
1397  
1398  
1398  
1399  
1399  
1400  
1401  
1402  
1403  
1404  
1405  
1406  
1407  
1408  
1409  
1409  
1410  
1411  
1412  
1413  
1414  
1415  
1416  
1417  
1418  
1419  
1419  
1420  
1421  
1422  
1423  
1424  
1425  
1426  
1427  
1428  
1429  
1429  
1430  
1431  
1432  
1433  
1434  
1435  
1436  
1437  
1438  
1439  
1439  
1440  
1441  
1442  
1443  
1444  
1445  
1446  
1447  
1448  
1449  
1449  
1450  
1451  
1452  
1453  
1454  
1455  
1456  
1457  
1458  
1459  
1459  
1460  
1461  
1462  
1463  
1464  
1465  
1466  
1467  
1468  
1469  
1469  
1470  
1471  
1472  
1473  
1474  
1475  
1476  
1477  
1478  
1479  
1479  
1480  
1481  
1482  
1483  
1484  
1485  
1486  
1487  
1488  
1489  
1489  
1490  
1491  
1492  
1493  
1494  
1495  
1496  
1497  
1498  
1498  
1499  
1499  
1500  
1501  
1502  
1503  
1504  
1505  
1506  
1507  
1508  
1509  
1509  
1510  
1511  
1512  
1513  
1514  
1515  
1516  
1517  
1518  
1519  
1519  
1520  
1521  
1522  
1523  
1524  
1525  
1526  
1527  
1528  
1529  
1529  
1530  
1531  
1532  
1533  
1534  
1535  
1536  
1537  
1538  
1539  
1539  
1540  
1541  
1542  
1543  
1544  
1545  
1546  
1547  
1548  
1549  
1549  
1550  
1551  
1552  
1553  
1554  
1555  
1556  
1557  
1558  
1559  
1559  
1560  
1561  
1562  
1563  
1564  
1565  
1566  
1567  
1568  
1569  
1569  
1570  
1571  
1572  
1573  
1574  
1575  
1576  
1577  
1578  
1579  
1579  
1580  
1581  
1582  
1583  
1584  
1585  
1586  
1587  
1588  
1589  
1589  
1590  
1591  
1592  
1593  
1594  
1595  
1596  
1597  
1598  
1598  
1599  
1599  
1600  
1601  
1602  
1603  
1604  
1605  
1606  
1607  
1608  
1609  
1609  
1610  
1611  
1612  
1613  
1614  
1615  
1616  
1617  
1618  
1619  
1619  
1620  
1621  
1622  
1623  
1624  
1625  
1626  
1627  
1628  
1629  
1629  
1630  
1631  
1632  
1633  
1634  
1635  
1636  
1637  
1638  
1639  
1639  
1640  
1641  
1642  
1643  
1644  
1645  
1646  
1647  
1648  
1649  
1649  
1650  
1651  
1652  
1653  
1654  
1655  
1656  
1657  
1658  
1659  
1659  
1660  
1661  
1662  
1663  
1664  
1665  
1666  
1667  
1668  
1669  
1669  
1670  
1671  
1672  
1673  
1674  
1675  
1676  
1677  
1678  
1679  
1679  
1680  
1681  
1682  
1683  
1684  
1685  
1686  
1687  
1688  
1689  
1689  
1690  
1691  
1692  
1693  
1694  
1695  
1696  
1697  
1698  
1698  
1699  
1699  
1700  
1701  
1702  
1703  
1704  
1705  
1706  
1707  
1708  
1709  
1709  
1710  
1711  
1712  
1713  
1714  
1715  
1716  
1717  
1718  
1719  
1719  
1720  
1721  
1722  
1723  
1724  
1725  
1726  
1727  
1728  
1729  
1729  
1730  
1731  
1732  
1733  
1734  
1735  
1736  
1737  
1738  
1739  
1739  
1740  
1741  
1742  
1743  
1744  
1745  
1746  
1747  
1748  
1749  
1749  
1750  
1751  
1752  
1753  
1754  
1755  
1756  
1757  
1758  
1759  
1759  
1760  
1761  
1762  
1763  
1764  
1765  
1766  
1767  
1768  
1769  
1769  
1770  
1771  
1772  
1773  
1774  
1775  
1776  
1777  
1778  
1779  
1779  
1780  
1781  
1782  
1783  
1784  
1785  
1786  
1787  
1788  
1789  
1789  
1790  
1791  
1792  
1793  
1794  
1795  
1796  
1797  
1798  
1798  
1799  
1799  
1800  
1801  
1802  
1803  
1804  
1805  
1806  
1807  
1808  
1809  
1809  
1810  
1811  
1812  
1813  
1814  
1815  
1816  
1817  
1818  
1819  
1819  
1820  
1821  
1822  
1823  
1824  
1825  
1826  
1827  
1828  
1829  
1829  
1830  
1831  
1832  
1833  
1834  
1835  
1836  
1837  
1838  
1839  
1839  
1840  
1841  
1842  
1843  
1844  
1845  
1846  
1847  
1848  
1849  
1849  
1850  
1851  
1852  
1853  
1854  
1855  
1856  
1857  
1858  
1859  
1859  
1860  
1861  
1862  
1863  
1864  
1865  
1866  
1867  
1868  
1869  
1869  
1870  
1871  
1872  
1873  
1874  
1875  
1876  
1877  
1878  
1879  
1879  
1880  
1881  
1882  
1883  
1884  
1885  
1886  
1887  
1888  
1889  
1889  
1890  
1891  
1892  
1893  
1894  
1895  
1896  
1897  
1898  
1898  
1899  
1899  
1900  
1901  
1902  
1903  
1904  
1905  
1906  
1907  
1908  
1909  
1909  
1910  
1911  
1912  
1913  
1914  
1915  
1916  
1917  
1918  
1919  
1919  
1920  
1921  
1922  
1923  
1924  
1925  
1926  
1927  
1928  
1929  
1929  
1930  
1931  
1932  
1933  
1934  
1935  
1936  
1937  
1938  
1939  
1939  
1940  
1941  
1942  
1943  
1944  
1945  
1946  
1947  
1948  
1949  
1949  
1950  
1951  
1952  
1953  
1954  
1955  
1956  
1957  
1958  
1959  
1959  
1960  
1961  
1962  
1963  
1964  
1965  
1966  
1967  
1968  
1969  
1969  
1970  
1971  
1972  
1973  
1974  
1975  
1976  
1977  
1978  
1979  
1979  
1980  
1981  
1982  
1983  
1984  
1985  
1986  
1987  
1988  
1989  
1989  
1990  
1991  
1992  
1993  
1994  
1995  
1996  
1997  
1998  
1998  
1999  
1999  
2000  
2001  
2002  
2003  
2004  
2005  
2006  
2007

## Example 1

Incident Radiation	House Roof Area	Total Incident Radiation	% efficiency of solar energy conversion to electricity	Electricity Generated	Electricity Consumed During Daylight hours <sup>3</sup>	Electricity available for methanol production	Hydrogen produced <sup>4</sup>	Methanol Produced <sup>5</sup> (as methanol)	Methanol produced (as methanol/water 50:50 mol % mixture)	Hydrogen generation/ methanol synthesis equipment Power rating
kW/m <sup>2</sup> /day	m <sup>2</sup>	kWh/day		kWh/day	kWh	kWh	kg	litres/day	kg/day	kW
5.0	130	650	17.1 <sup>1</sup>	111.2	25	86.2	1.31	8.4	6.6	12.1
5.0	100	500	33.0 <sup>2</sup>	165	25	140	2.13	13.6	10.8	19.7

## Notes

- The Kyocera Corporation of Japan holds the world record for conversion efficiency in a multicrystal photovoltaic cell of 17.1%. Source: Kyocera Advertising literature.
- The Swiss Federal Institute of Technology has recently announced solar cells based on Titanium Dioxide which have efficiencies as high as 33% (New Scientist, No. 2155, p 11, 10 October 1998).
- The average house in the USA consumes 18800 kWh energy per annum. This figure has been divided by 365 days and the result split equally between day and night. Source: The North Carolina Solar Centre.
- Assuming an electrolysis cell efficiency of 60%. Higher Heat Value (HHV) per kg of hydrogen = 39.4 kWh.
- Assuming a 95% conversion yield.

## Option 1: methanol used as power storage for night usage

Electricity consumed during night time	kWh/day	25	25	55% Conversion methanol to electricity (assuming a 55% efficiency for a methanol fuel cell)
Methanol consumed at night	kg	8.2	8.2	Conversion of methanol to electricity, Lower Heat Value (LHV) = 5.53 kWh/kg of methanol
Deficit (-)/Excess Methanol	kg	-1.6	2.6	

## Option 2: off-peak electricity used to generate methanol at night

Off-peak power consumed	kWh	80	119	
Methanol synthesised from off-peak electricity	kg	6.2	9.2	
Methanol produced from solar electricity	kg	6.6	10.8	
Total methanol fuel available for use in an Internal Combustion Engine (ICE) per day	1	16.2	25.2	
Methanol/water fuel available for ICE per day	1	23.4	36.4	

- 23 -

The amount of methanol produced and stored during the day may not be sufficient to meet the full electricity demands of a house during the night. In such situations, the shortfall in electricity may be 5 made up using cheap nighttime electricity from the national grid. Cheap nighttime electricity may also be used to produce further methanol for storage. Stored methanol may be used to generate electricity as required, for example during the day when the cost of 10 electricity from the national grid is higher (option 1) or may be used for some other purpose, for example in an internal combustion engine (option 2).

In situations where the amount of methanol produced 15 and stored during the day exceeds the amount needed to generate electricity to meet nighttime demand, any excess electricity may be exported to the national grid, or the methanol stored to meet future electricity demand. Alternatively, excess methanol may be used for some other purpose, for example in a methanol fuel cell 20 or an internal combustion engine to power a vehicle.

TAKEN - SEARCHED - INDEXED -